# NASA's New Millennium Program: Flight Validation of Advanced Technologies for Space Applications

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*Abstract*--NASA's New Millennium Program (NMP) was created to accelerate the insertion of advanced spacecraft and instrument technologies into future science missions by validating these technologies on deep space and Earth-orbiting technology validation missions. This paper describes the currently approved NMP flight projects and briefly describes the processes used to select and validate their associated technologies. Future NMP flight opportunities are also discussed.

TABLE OF CONTENTS



## 1. INTRODUCTION

In 1995 the National Aeronautics and Space Administration (NASA) created the New Millennium Program. The objective of this program is to conduct space flight validation of breakthrough technologies that will significantly benefit future space- and Earth-science missions. The breakthrough technologies selected for validation must 1) enabling new science capabilities to fulfill NASA's Space and Earth Science Enterprise' objectives and/or 2) reducing the costs of future space and Earth science missions. A secondary objective is to return high priority science data to the extent possible within mission and cost constraints. The Jet Propulsion Laboratory (JPL) was assigned to manage the program for NASA.

The goal of space flight validation of these technologies is to mitigate the risks to the first users and to promote the rapid infusion of these technologies into future science missions. Investments made by the NMP will accelerate the insertion of these high-value, breakthrough technologies into the space and Earth science missions thereby leading to significant improvements in scientific capabilities and mission cost effectiveness. Additional information on the New Millennium Program is available on the Internet [1].

The first generation NMP missions were designed to provide a comprehensive, system-level validation of suites of interacting , high-priority spacecraft and measurement technologies. The second generation NMP missions were designed to....... While the NMP plans to continue flying these system-level technology validation missions where appropriate, this approach is being augmented with more highly focused, component-level validation flights of breakthrough technology subsystems. Brief descriptions of the first and second generation NMP flights are given below. We then describe the system and subsystem validation objectives for future NMP flight validation opportunities. Finally, we briefly describe the processes used to select technologies for validation on NMP missions.

## 2. FIRST GENERATION VALIDATION FLIGHTS

### *Deep Space 1 (DS1)*

Deep Space 1, the first of the New Millennium missions, was launched from the Kennedy Space Center on 24 October 1998. This spacecraft, depicted in Figure 1, carries a complement of 12 technologies for validation during the following ten months after launch. These technologies are: 1) ion propulsion system (IPS) with a suite of diagnostic sensors, 2) solar concentrator arrays, 3) autonomous optical navigation, 4) miniature integrated camera spectrometer (MICAS), 5) plasma experiment for planetary exploration (PEPE), 6) small deep space transponder (SDST), 7) Ka-band solid-state power amplifier (SSPA), 8) beacon monitor operations, 9) autonomy remote agent experiment, 10) silicon-on-insulator low-power electronics experiment, 11) multifunctional structure, and 12) power activation and switching module. These technologies are described in more detail in reference 2.

The ion propulsion system (IPS) offers significant mass savings for future space missions with high $\Delta V$ requirements. This propulsion system uses Xenon as the propellant, and at peak operating power consumes 2.3 kW and produces 92 mN of thrust at a specific impulse of 3100 s. Thrust levels are controlled by balancing thruster and propellant feed parameters at lower power levels. At the lowest thrust level, 20 mN, the power consumption is 0.5 kW at a specific impulse of 1900 s. The diagnostic sensors will aid in quantifying the interactions of the IPS with the spacecraft, including the advanced-technology science

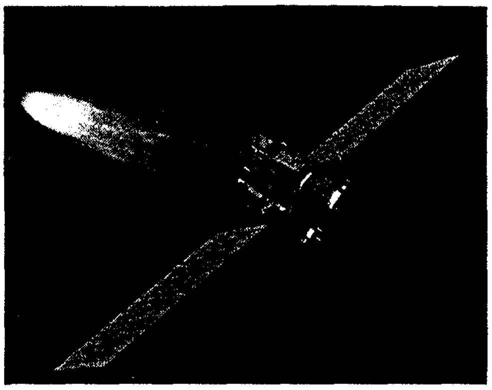

Figure 1. Deep Space 1 contains 12 technologies for space flight validation. The spacecraft intercepted Asteroid 1996 Braile in July 1999, and the technology validation mission was completed the following September. The Deep Space 1 is now a science mission with the objective of intercepting Comet Borrelly in 2001.

instruments, and in validating models of those interactions.

*The Ion Propulsion System (IPS):* Once in space the IPS got off to a shaky start, shutting down automatically after only 4.5 minutes of operation. This shutdown was attributed to a short circuit caused by a piece of conductive debris trapped between the ion engine's closely-spaced (0.6 mm) ion acceleration grids. To dislodge the debris, the grids were thermally cycled, causing them to move relative to each other. After this process was repeated several times, the engine started normally. Since then, it has worked flawlessly throughout the validation flight and well into the extended mission. At the time of writing, the IPS has logged more than 230 days of operation in space, far longer than any other space propulsion system.

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*Solar Concentrator Arrays*: Because ion propulsion systems require large amounts of electric power, a high power solar array was required to validate the IPS. The solar array technology adapted for DS1 was the Solar Concentrator Array with Refractive Linear Element Technology (SCARLET) array, which was sponsored by the Ballistic Missile Defense Organization (BMDO). This solar array uses cylindrical silicone Fresnel lenses to concentrate sunlight onto 3600 dual junction $GaInP_2/GaAs/Ge$ solar cells arranged in strips. The solar array produces 2.5 kW at 1 AU and consists of two wings each of which consist of four (113 cm x 160 cm) panels that are folded for launch. When fully extended, the wings measure 11.8 meters from tip to tip.

SCARLET was the first concentrator array used for primary power on a spacecraft. This technology was extensively tested on DS1, validating the performance of the multi-junction cells, the Fresnel optics and their innovative deployment approach, and the compatibility of their electrical design with the IPS.

*Autonomous Optical Navigation*: The autonomous optical navigation (autonav) system has piloted the spacecraft from shortly after separation from the launch vehicle through the encounter with Asteroid Braille and is currently being used for navigation to the planned encounter with comet Borrelly in September 2001, as part of the extended mission. Autonav uses data stored in the flight computer as well as data acquired and processed during the mission. The stored data consists of the spacecraft trajectory (generated and optimized on the ground), the ephemerides of the target bodies, about 250 "beacon" asteroids, and all planets (except Pluto) as well as the positions of about 250,000 stars. During the mission, once or twice each week, the spacecraft is turned to point the MICAS sequentially at 4 to 20 "beacons". Visible images from the MICAS are processed and combined with other information to determine the location of the spacecraft.

Autonomous navigation worked flawlessly during most of the validation flight, but miss-targeted the images scheduled for closest approach to asteroid Braille during the flyby on 29 July 2000. This tracking problem apparently resulted from the MICAS camera's inability to reacquire this dim object after the spacecraft recovered from a safing event that occurred a few hours before the encounter. The autonave software has since been updated to address these and other challenges faced during the validation flight, producing a much more robust product for future deep space missions.

*The Miniature Integrated Camera and Spectrometer (MICAS):* MICAS is an advanced 12-kg instrument that includes 2 visible imaging channels, an ultraviolet (UV) imaging spectrometer, and a short-wave infrared (SWIR) imaging spectrometer. All sensors share a common 10-cm-diameter telescope. This instrument contains no moving parts, and the structure and optics are fabricated from thermally stable silicon carbide.

The two MICAS visible imaging channels and the SWIR imaging spectrometer were successfully validated in flight, but the quality of their data was seriously compromised by scattered light in the instrument. This scattered light was attributed to a poorly designed solar calibration port and sun shade. The UV channel could not be validated because the detector (a frame transfer CCD) failed early in the mission.

*The Plasma Instrument for Planetary Exploration (PEPE):* PEPE combines several plasma physics instruments in one compact 5.6-kg package to determine 3-dimensional plasma distribution over its $4\pi$ steradian field of view. This instrument also provides information about the plasma environment associated with the IPS and its interactions with spacecraft surfaces and instruments and with the solar wind.

PEPE data taken in the vicinity of Earth was validated directly through comparisons with measurements from plasma instrument on other spacecraft (ACE, WIND, and Cassini). PEPE measurements also confirmed that high quality plasma measurements could be obtained at energies greater than 50 eV while the IPS is operating. Below this energy, PEPE also measured xenon ions and secondary electrons from the IPS and SCARLET arrays.

*Small Deep Space Transponder (SDST)*: Three telecommunications technologies were included on the DS1 for validation. The small deep-space transponder combined the receiver, command detector, telemetry modulator, excitor, beacon tone generator (for beacon monitor operations, another technology validated on the mission), and control functions into one 3-kg package. The SDST allows X-band uplink and both X-band and $K_a$-band downlink.

All SDST functions for uplink, downlink, and radio ranging were thoroughly validated in flight, including the optional Ka-band downlink capability. These validation activities reduced the risk of this advanced telecommunications technology sufficiently that the SSDST has been adopted by the baseline on the Mars '01 Orbiter and SIRTF.

*Ka-Band Solid State Power Amplifier (KAPA):* The Ka-band (32-GHz) solid-state power amplifier has a potential for providing a 4-fold increase in the data rate when compared to conventional X-band systems. KAPA is the highest power device of this type ever used for deep space communications. Its key technology is 0.25μm GaAs Pseudomorphic High Electron Mobility Transistors (PHEMT). KAPAs mass was 0.66 kg, its RF output power was 2.2 W, and its gain was 36 dB. In flight, KAPA operated nominally, and was power cycled 28 times, accumulating over 1680 hours of operation.

*Beacon Monitor Operations Experiment*: The SDST generates tones used for beacon monitor operations, an operational concept conceived to reduce the heavy demand expected on the DSN if many missions are flown simultaneously. In this operations concept, an on-board data summarization system determines the overall health of the spacecraft and then transmits one of four tones to indicate to the operations team (on Earth) the urgency of the need for DSN coverage for the spacecraft. Because they lack data modulation, these tones are easily detected with small, low-cost systems, reserving the large, expensive DSN stations for command uplink and data reception when the beacon indicates that such attention is required.

The DS1 flight allowed a complete, end-to-end validation of the Beacon Monitoring Experiment. Validation tests included tone transmission and detection, engineering summary generation and visualization, and tone message handling and reporting among other capabilities.

*The Remote Agent Experiment (RAX):* The remote agent experiment is an on-board artificial intelligence system for planning and executing spacecraft activities. This technology uses developd and executes a mission plan expressed as high-level goals. A planning and scheduling engine uses the goals, comprehensive knowledge of the state of the spacecraft, and constraints on spacecraft operations to generate a set of time-based activities that are delivered to the executive. The executive then creates a sequence of commands that are issued directly to the appropriate destinations on the spacecraft. The executive monitors the responses to the commands and reissues or modifies them as required. A mode identification and reconfiguration engine aids in assessing the spacecraft state and in recovering from faults without requiring help from the ground, except in extraordinary cases.

RAX was tested for several days on DS1, in a series of scenarios based on active cruise mode. In these tests, it commanded a subset of the spaceraft subsystems, including the IPS, MICAS, autonav, attitude control system, and a series of power switches. The goal of these tests was to execute an IPS thrust arc, acquire optical navigation images as requested by the autonav system, and respond to simulated faults. After a few bugs were fixed, the RAX satisfied 100% of its flight validation objectives. It has since been awarded the NASA 1999 Software of the Year Award.

*Low Power Electronics Technologies*: The low-power electronics experiment was developed to characterize the effects of the space environment on sub 0.25μm fully depleted silicon-on-insulator CMOS test devices that operate at supply voltages of less than two volts. This experiment functioned nominally throught the DS1 flight.

*Multifunctional Structures (MFS)*: The multifunctional structure is an experiment to evaluate the concept of folding spacecraft electronics into the walls of the spacecraft, thereby saving weight and space by eliminating chassis, cables and connectors. The MFS on DS1 was sponsored by the Air Force Research Laboratory Phillips Laboratory (AFRL/PL). It incorporated 2-D and 3-D multi-chip modules, and flex circuit interconnects along with advanced composites and thermal management systems. Once in flight, the MFS experiment was powered up once every two weeks, and two experiment cycles were run during each test. The validation was a complete success.

*Power Activation and Switching Module (PASM):* The power activation and switching module combines advamced mixed signal ASICs and high-density interconnect technologies to enable significant miniaturization of spacecraft electrical load and switching functions by eliminating bulky relays and fuses that have been used in the past. Each of PASM's 4 switches could isolate faults, limit in-rush and fault currents, and supply voltage and current telemetry and perform other functions. They could switch from 30 to 40 V at up to 3 amps. The PASM switches were successfully exercised several times during the DS1 flight and showed no performance degradation.

Detailed descriptions of these technologies are available on the JPL Technical Reports Server [3], and operational results from the DS1 technology validation mission are summarized in reference 4.

## *Deep Space 2 (DS2)*

Deep Space 2, the second of the New Millenium missions, was launched from the Kennedy Space Center on 3 January 1999 and arrived at Mars the on 3 December 1999. The objective of this mission was to demonstrate: 1) key technologies that enable future network science missions (such as multiple landers, penetrators or spacecraft), 2) a passive reentry system, 3) highly integrated microelectronics capable of surviving high-g impact and operation at extremely low temperatures, and 4) in-situ subsurface data acquisition. The primary science objectives were to determine if water ice is present below the Martian surface and to characterize the thermal properties of the Martian subsurface soil.

This mission consisted of two indentical, 3-kg microprobes, one of which is shown in Figure 2, attached to the cruise stage that also carried the Mars 98 Polar Lander spacecraft. Approximately 10 minutes prior to landing, the probes were to separate from the cruise stage, descend through the atmosphere without the benefit of either parachutes or airbags, and survive a high-g impact near the northern boundary of the southern Martian polar region. The probes are protected during entry in the Mars atmosphere by a advanced non-ablative heat shield. At impact on the Martian surface, the heat shield was designed to shatter, and the probes were designed to separate into two parts. One part (the aft-body) was to remain on the surface and the other part (the fore-body) was designed to penetrate approximately 1 meter into the Martian soil. The fore- and aft-bodies are expected to experience shock loads of about 30000 g's and 60000 g's respectively.

The fore-body included a novel drill mechanism to acquire sub-surface samples and place them in a small crucible. The crucible was to then be heated to release water is any is present. A tunable diode laser was used to detect the presence of water vapor in the evolved gases. The fore-body also included temperature sensors to measure the vertical temperature gradient in the soil. Data from these instruments was to be transmitted via a advanced multi-layer flex cable to a radio beacon in the aft-body. The beacon was to relay the data to the Mars Global Surveyor spacecraft, which, in turn, was to relay the data back to Earth. The aft-body also included the lithium/thionyl chloride primary batteries, which supplied power to the probes.

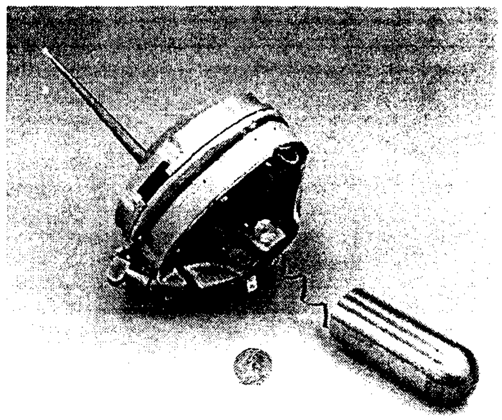

Figure 2. Deep Space 2 Mars Microprobe. At impact, the aft-body (left) will remain on the Martian surface, and the fore-body (right) will penetrate into the subsurface soil to detect the presence of water. A multi-layer flex cable connects the two sections electrically.

Microelectronics were to play a key role in the Deep Space 2. The microelectronics technologies to be validated on this mission were 1) an advanced microcontroller, 2) a power control unit, and 3) the evolved water experiment with its associated electronics. All of these technologies were located in the fore-body. The advanced microcontroller was to control operation of and store data produced by the evolved water experiment and the temperature sensors and send the data to the radio beacon for transmission to the Mars Global Surveyor. The power control unit was to provide power management , distribution and voltage conversion for the evolved water experiment, temperature sensors and the advanced microcontroller. Some of the unique electronics packaging aspects of the electronics in both the fore-body and the aft- body are described in reference 5.

Contact was never established with the DS2 microprobes after they landed on Mars. The exact cause of this problem has not yet been determined.

## *Earth Orbiting 1 (EO1)*

Earth Orbiting 1, the third of the New Millennium missions is scheduled for launch from Vandenberg Air Force Base in November 2000 (Figure 3). This validation flight includes three advanced imaging instruments and eight advanced spacecraft technologies. The three instruments, the Advanced Land Imager (ALI), the Atmospheric Corrector, and the Hyperion (hyperspectral imager) will lead to a new generation of high performance, low mass, low cost instruments for future Landsat type instruments executed by NASA's Earth Science Enterprise. The ALI employs novel wide-angle optics and a highly integrated spectrometer with a panchromatic channel. EO1 ALI flight validation is

Figure 3. Earth Orbiting 1. This spacecraft will validate technologies contributing to the reduction in cost of future Landsat missions.

designed to demonstrate spectral and spatial performance comparable to or better than Landsat 7, with substantial mass, volume and cost savings. Earth imagery is degraded by atmospheric absorption and scattering. The EO1 Atmospheric Corrector is a compact, low-resolution imaging spectrometer designed to provide the first space-based test of an Atmospheric Corrector for increasing the accuracy of surface reflectance estimates. The Hyperion is a hyperspectral imager capable of resolving 220 spectral bands at wavelengths between 0.4 to 2.5 µm. Its spatial resolution is 30 meters over a 100-km swath.

The advanced spacecraft technologies include a X-band phased array antenna, a carbon-carbon composite radiator, a lightweight flexible solar array, a pulsed plasma thruster and enhanced formation flying capablility will enable smaller, lower weight and reduced spacecraft power buses. A wide band advanced recorder processor (WARP) receives data from the three instruments at up to 840 Mbits/sec, then formats and stores the data in its 40 Gbit solid-state recorder. The WARP includes a lossless data compression chip and a 10 MIP processor capable of processing science data. The data will be sent to the ground via the X-band phased array antenna at 105 Mbits/sec and subsequently sent to GSFC for technology validation and science research. Parallel EIA RS-422 interfaces provide the data path between each of the three instruments and the WARP.

To validate the advanced instruments, EO1 will fly in formation with the Landsat 7, providing at least 200 paired scene comparisons with that satellite's Enhanced Thematic Mapper + (ETM+) instrument.

## 3. Second Generation Validation Flights

*Space Technology 5 (ST5)*

The Space Technology 5 (ST5) mission will fly three miniature (~22 kg) spacecraft in a highly elliptical orbit around the Earth. The ST5 Nanosat Constellation Trailblazer Mission is scheduled for launch (as a secondary payload) in 2003. This NMP flight will validate technologies needed for future constellations of spacecraft that are neded for studies of the magnetoshpers of the Earth and other planets. ST5 will validate a suite of 8 advanced technologies, including:

- A formation flying and communications instrument, can communicate between spacecraft and determines their positions using the Global Positioning System (GPS)
- Autonomous ground station software for scheduling and orbit determination of constellations of spacecraft
- A X-band transponder that requires ¼ the voltage and half the power, weighs 12 times less and is nine times smaller than proven technology
- Advanced multifunctional structures that provide electrical interconnects and reduce cable mass
- An ultra low-power electronics experiment that uses a field programmable gate array (FPGA) that is more reliable and uses 1/20 the power of proven technology
- Variable emittance coatings that are electrically tunable, such that they can change their optical properties to absorb the Sun's heat when the spacecraft is cool or to reflecting or emitting heat to cool the spacecraft
- A miniature microelectromechanical system (MEMS) chip that provides fine attitude adjustments on the spacecraft using 8.5 times less power and weighing less than half as much as proven technology
- A lithium-ion power system for small satellites that stores two to four times more energy and has a longer life than proven technology

This mission will also validate manufacturing methods needed to produce large numbers of spacecraft.

*Earth Orbiting 3 (EO3)*

The Earth Orbiting 3 mission will fly the Geosynchronous Imaging Fourier Transform Spectrometer (GIFTS) and 6 other advanced technologies to enable improved remote sensing of clouds, moisture, and winds in the Earth's atmosphere. These capabilities are needed for improved weather forecasting and to provide additional constraints on atmospheric trace gases. GIFTS will b e carried to geosynchronous orbit in late 2004 as a secondary payload on a satellite provided by the US Navy Office of Naval Research. The EO3 GIFTS mission will provide a system-level validation of 7 advanced technologies including:

- A high spectral resolution, imaging Fourier transform interferometer
- High speed, on-board signal processing
- Advanced cryogenic cooling
- Data compression
- Autonomous pointing and control

- Low-power radiation-tolerant microelectronics
- Lightweight structures and optics

As a by-product of this technology validation flight, GIFTS will return valuable scientific data that will enable the development and validation of improved strategies for monitoring atmospheric temperatures, water vapor content, trace gas amounts, and winds from geostationary orbit. For example, while existing geostatonary instruments can provide data need to infer winds by tracking clouds, the high resolution, spatially resolved GIFTS spectra should also reveal water vapor variations in clear skies that can be tracked to yield information on winds as well.

## 4. FUTURE NMP FLIGHT OPPORTUNITIES

The first and second generation NMP flights described above were designed to provide a comprehensive, system-level validation of suites of interacting technologies. This technology validation approach is essential in some circumstances, but it is not necessarily the most efficient approach for other technologies. For example, the combination of the Ion Propulsion system, the SCARLET concentrator arrays, and the Autonav system was a particularly expedient approach for validating the DS1 solar electric propulsion system. However, other DS1 technologies, such as the low power electronics or the multifunctional structures experiment, as well as a broad range of other technologies currently in development could be successfully validated as individual components or subsystems on a broad range of platforms.

These considerations suggest that it would be possible to accelerate the rate of technology infusion into future missions by augmenting NMP's existing system-level validation flights with a low-cost, quick-turnaround "subsystem mode" that would include stand-alone validations of a range of payloads, from components to complete subsystems. These flights would focus specifically on technologies that:

- Require a validation in space to mitigate risks to first science users (e.g., environmental effects, incorporate a major implementation shift, etc.)
- Enable critical measurements or spacecraft capabilities
- Yield broad benefits to multiple users,
- Can be tested as stand-alone components without extensive interactions with other parts of the payload.

By focusing on the specific components of an advanced spacecraft subsystem or instrument that requires a flight validation, this approach should:

- Enhance the validation rate by allowing components to be flown on the first available flight, thus precluding the need to wait for the development of a range of other technologies
- Be more cost effective, because it minimizes the investment in low-tech components or technologies that do not need to be validated in space

To achieve the greatest benefit from this approach, the NMP is currently working with other NASA programs and with other government agencies to identify flights of opportunity that could be exploited for component-level flight validations. The program is also studying the feasibility of a general-purpose technology validation bus, or "space truck" that could be used to validate technologies for NASA's Space and Earth Science programs, as well as technologies contributed by our partners from other government agencies.

In spite of its potential advantages, this subsystem mode cannot satisfy all of NASA's needs for technology validation. The NMP therefore plans to continue to conduct system-level validation flights. These flights are of particular value for testing advanced technologies that represent a system-level paradigm shift in implementation or operations approach or measurement concept. For example, a system level validation might be needed to validate the use of a coordinated network of spacecraft, rather than a single platform to make a particular measurement (e.g., Magnetospheric Constellation, Terrestrial Planet Finder, or Mars surface weather or seismic Networks). In other cases, a system-level validation of an advanced instrument might be needed to minimize the risk and insure the continuity of a critical measurement (e.g., Landsat, operational weather satellites)

To address these needs, and to insure the highes possible rate of technology infusion within the current budget, the NMP is sharpening its critieria for technology validations, to yield a balanced mix of subsystem and system-level validation flights. The first sub-system validation flight for the NASA Office of Space Science is currently under way, and will constitute Space Technology 6 (ST6). In the future, we anticipate that we will call for subsystem flights about once a year. System-level flights will be conducted at intervals of 18 months to two years.

## 5. TECHNOLOGY SELECTION PROCESSES FOR NMP VALIDATION FLIGHTS

*Integrated Product Development Teams and Technology Selection for First Generation NMP Missions*

For the first three and a half years of the NMP, technology selection for flight validation was focused in six technology thrust areas: Autonomy, Telecommunications, Modular and Multifunctional Systems, Microelectronics, In-Situ Instrument and Micro-electromechanical Systems, and Instrument Technologies and Architectures. For each thrust area, teams consisting of representatives from government, academia, federally-funded research and development centers, and industry were formed. These teams, referred to as Integrated Product Development Teams (IPDTs), operated as consortia to identify breakthrough technologies, prepare technology roadmaps, and develop flight hardware and software to validate these new enabling technologies in a cooperative and collaborative fashion. Non-NASA members offered specific technologies of interest to the NMP and were selected through a formal source selection process. The organizational membership of these IPDTs is described in more detail in reference [10].

The IPDTs proposed technologies to be incorporated to be incorporated into the first generation of deep space (DS1 and DS2) and Earth-orbiting (EO1) validation missions which were described above. The proposed technologies were to be funded early enough in the NMP program schedule so that the new technologies did not adversely affect the schedules of the flight projects using the new technologies. The proposed technologies were evaluated for their potential benefit and impact on cost, schedule and overall risk at the end of the concept development phase for each project. The selected technologies were then incorporated into the baseline architecture for these three flight projects. Those high risk technologies that encountered unforeseen development problems during project implementaton were deleted from the project baseline architecture to lessen cost and schedule risk.

For those technologies included in the final hardware configuration of a flight project, technology validation agreements were negotiated between the technology providers and the flight project office. These agreements defined the success criteria and quantitative performance goals to be achieved in order to successfully validate a technology. In addition, the data obtained from these technologies are to be analyzed and disseminated to interested organizations/parties by means of appropriate workshops, NMP technology validation symposia, formal technology validation reports, and peer-reviewed journal papers.

*Technology Selection for Second Generation Missions and for Future NMP Flight Opportunities*

Subsequent to the establishment of the New Millennium Program in 1995, the NASA Strategic Plan [5] was published. This plan defines the Agency vision, mission, and fundamental questions of science and research that are the foundation of Agency goals to be accomplished over the 25 years spanning 1998 to 2023. This plan also describes the four Strategic Enterprises to manage programs and activities that will implement the Agency mission. The Strategic Enterprises are Space Science, Earth Science, Human Exploration and Development of Space, and Aeronautics and Space Transportation Technology. These enterprises have published their respective strategic plans that include comprehensive science and focused technology roadmaps for proposed future missions.

NASA also created the Cross-Enterprise Technology Development Program (CETDP) to focus on technology development in support of multiple Enterprise customers. Typically, CETDP acts to develop critical space technologies that enable innovative and less costly missions and enable new mission opportunities through revolutionary, long-term, high-risk, high-payoff technology advances. Many of these technologies are at the very early stages of development and may be viewed as technologies of opportunity ("technology push") rather than as required technologies identified in the Enterprise focused technology roadmaps.

The NASA Strategic Enterprises and the CETDP are now responsible for developing technology roadmaps that were previously a key function of the NMP IPDTs. In addition the technology acquisition process for future NMP flight projects was simplified by using mission specific technology solicitations. As a result, the IPDTs have been disbanded. NMP has subsequently developed a new process for selecting technologies for space flight validation and formulating technology validation missions that will support the goals of the Space Science and Earth Science Enterprises. These processes are outlined below and described in detail in reference 8.

*Flight Validation Domain*—The number of systems, subsystems, or components that might be flight validated is very large. The reasons for flight validation range from "cannot be tested on the ground" to "lack of flight heritage" due to an advance in the technology or to procedural change in hardware assembly or mission operations. Thus, a rational and equitable selection process is required to allow an orderly and open selection of technologies for flight validation on NMP missions.

As depicted in Figure 4, the technology selection process begins with aligning emerging technologies being developed by NASA, other government agencies, universities and industry with the science capability needs of the Space and Earth Science Enterprises. Emphasis is placed on identification of emerging high-risk, high-payoff breakthrough technologies. Using flight validation justification factors, described in reference 8, the candidate breakthrough technologies for flight validation are identified, and NMP will flight validate only a small portion of those candidate technologies.

*Technology Selection Process*—The NMP process for planning and implementing technology validation flights is shown as a high-level block diagram in Figure 5. The process essentially consists of four major activities: (a) a "pre-project" planning activity for identifying and capturing candidate concepts, (b) establishing teams to study candidate concepts, (c) studying the concepts in detail, and (d) selecting one concept for continuation into project formulation, implementation, flight and dissemination of flight test results.

The process for identifying flight validation technologies and assimilating them into candidate flight validation

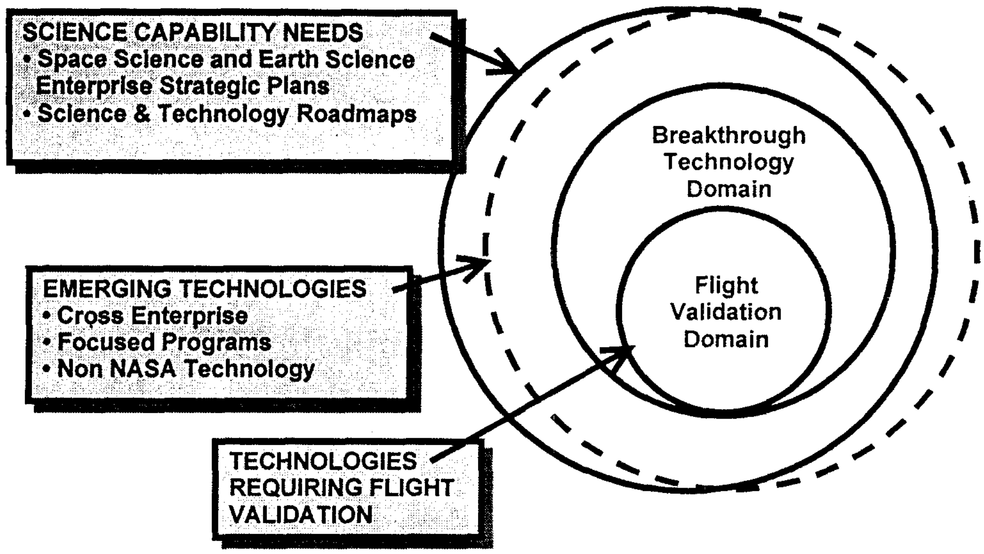


Figure 4. The relationship between the technology development domain and the identification of candidate technologies for space flight validation on NASA NMP missions.

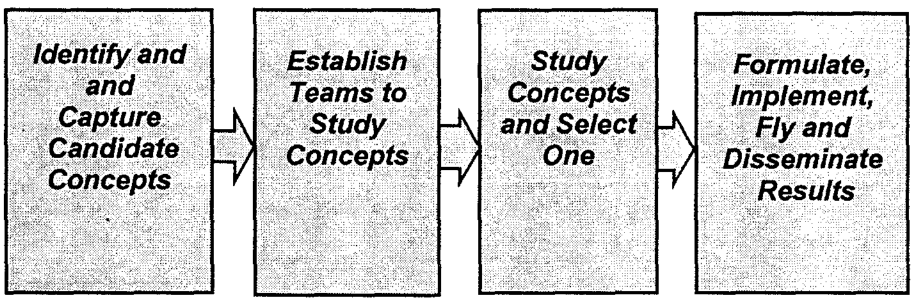


Figure 5. NMP planning and implementation processes for technology validation flights.

missions begins with the NASA Enterprise Theme technologists reviewing the technology and capability needs identified in the Strategic Enterprise (science and technology pull) roadmaps and compiling a capability needs inventory for each Theme.

In parallel, the NMP staff compiles a list of candidate technologies for flight validation from information in the NASA Technology Inventory. This compilation step is constrained and guided by several factors: (a) breakthrough technology considerations, (b) generic nature of the technology, (c) flight validation justification factors, (d) risk identification, and (e) TRL (Technology Readiness Level). Breakthrough factors include considerations such as technology performance and cost. The generic nature is determined by the support shown by the Enterprise Theme technologists. The risk identification factors are customer focused and are meant to determine the degree to which the technology will be utilized. The maturity of the technology is indicated by the Technology Readiness Levels described in reference 8.

The justification factors are a key requirement in the technology selection process. These factors (environmental, paradigm shift, and interdependency/complexity) are discussed in detail in reference 8. Only one of these factors is necessary to justify flight validation.

The capability needs list compiled by the Theme Technologists is then combined with the list of candidate technologies compiled by the NMP staff. The results are then assimilated into a list of candidate flight validation concepts with the concurrence of the Theme Technologists, the CETDP thrust area managers and the NMP staff. The list of candidate flight validation concepts is also made available to the non-NASA technical community for informal comment and feedback on relevant technology developments taking place outside NASA.

*Flight Project Formulation and Implementation*--The candidate flight validation mission concepts are further refined using feedback received from the non-NASA technology community and programmatic priorities and constraints established by NASA Headquarters. Several of these concepts are then selected and a report on the selected concepts is prepared by the NMP staff. This report contains details on the approach for each proposed mission, the technologies bundled in each concept and the risk reduction approach for each concept. This report is submitted to NASA Headquarters for review, and two or more of these concepts are then selected for continuation into the project formulation phase.

The NMP staff then uses a competitive solicitation process to form concept study teams. Membership in these study teams is open to US industry and academia, NASA centers, other US government agencies, non-profit organizations, and Federally-Funded Research and Development Centers (FFRDCs). These organizations are encouraged to propose technologies that meet the needs of the mission concepts described in the technology announcement. The proposed technologies should be at technology readiness level 3 or 4 and have a realistic plan to reach level 7 in time to support launch of the mission. The proposals are peer-reviewed, and recommendations for membership on the concept study teams are made by NASA Headquarters. Formal membership selection is made by the NMP. NASA Headquarters also assigns leadership responsibility to a NASA center for each of the concept study teams.

Each of the concept study teams work to refine their respective concepts and develop a detailed concept proposal. During this study phase it may be found that all of the technology validation goals cannot be achieved due to either funding or technology readiness constraints. Thus it is possible that some of the technologies selected will not be included in the final concept proposal. The suppliers of those technologies that are included in the final concept proposal will be funded to supply the flight articles if the concept is selected for detailed project formulation.

Once a flight validation concept is selected, a solicitation for a spacecraft bus provider will be conducted if this is required for the mission. A detailed project plan is prepared. This plan includes detailed schedules, cost estimates, a technology validation plan including technology validation agreements with the technology suppliers, a technology infusion plan, and a risk management plan. At this point, if there is sufficient justification, science instruments may be included in the mission. The science instruments will re acquired through the standard NASA AO (Announcement of Opportunity) process. These plans are submitted to NASA Headquarters for approval, implementation of detailed design, fabrication, and software development activities take place. If science measurements are included in the mission, the science team is formed by means of the NASA AO process. After the mission is completed, the technology validation results are dissemenated by the means mentioned previously.

## 4. Summary

Technology validation for future NASA science missions is a complex process that requires careful planning and execution. NASA created the New Millennium Program in 1995 to perform the technology validation needs for the NASA Office of Space Science and Office of Earth Science. The technology acquisition process used during the first two years of the NMP for the first three NMP missions (DS1, DS2, and EO1) as well as some details of the technologies included in these projects were described. The refined NMP technology acquisition process was then described in detail with particular attention being paid to the "up front" planning activities (shown in Figure 7a) for mission concept development. The processes related to concept study team formation, technology acquisition, and concept selection for flight implementation were successfully implemented for the ST5 and EO3 projects.

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